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Technical Report No. 86

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B.R. Barwell and C. Bradbury
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Meteorological Office
London Road
Bracknell
Berkshire
RG12 2SZ
United Kingdom

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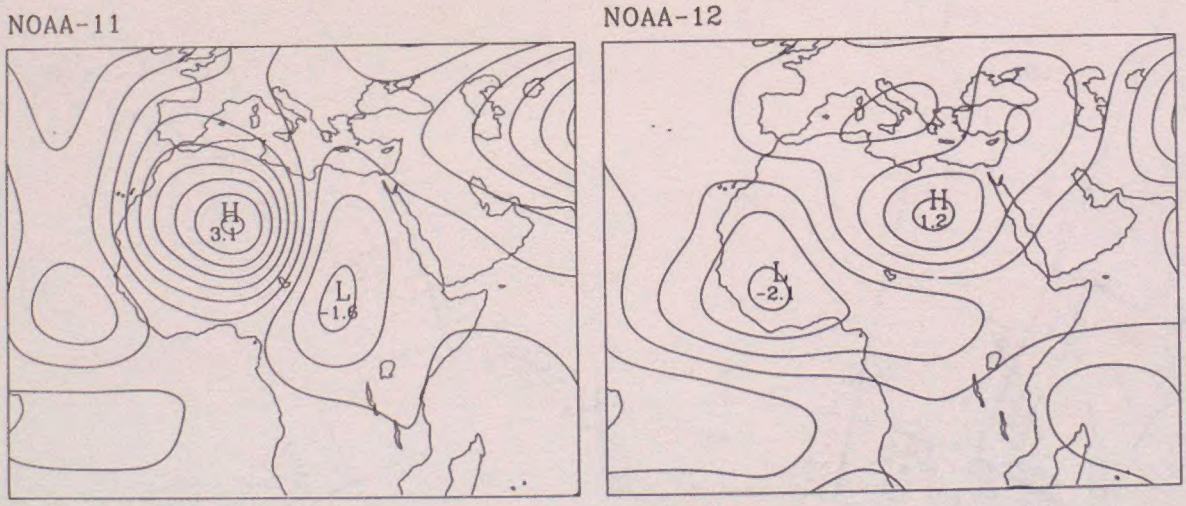

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1. Satellite soundings in the Met. Office

Each member of the NOAA series of operational polar orbiting satellites carries instruments for retrieving atmospheric temperature and moisture profiles. Known as the TIROS Operational Vertical Sounder (TOVS), the instrumentation consists of three separate sounders, a High-resolution Infra-Red Spectrometer (HIRS), a Microwave Sounding Unit (MSU) and a Stratospheric Sounding Unit (SSU) (Smith *et al.* 1979).

Retrieved profiles have been produced from locally received TOVS data for operational use in the Meteorological Office since the early 1980s. The data is picked up by the satellite receiving station at Lasham when either of the satellites is above the horizon. The retrieval is currently performed using a linear technique (Rodgers 1970) which requires initial processing and removal of the effect of clouds from the infra-red readings (Eyre and Watts 1987) but there are plans to change to the non-linear scheme referred to below using unprocessed data. The system is known as the Local Area Sounding System (LASS).

More recently, global coverage has been possible using data provided by the National Environmental Satellite Data Information Service (NESDIS). In this data each field of view is classified as cloud-free, cloudy or partly cloudy and observations are corrected for scan angle and, where possible, the HIRS data are corrected for cloud contamination. MSU and SSU data are given for all fields of view and HIRS for all except cloudy fields of view. The data resolution is about 120km and the data volume is currently about 75000 soundings per day. Figure 1 shows a typical coverage of the data for a 24-hour period. To process this data, the Met. Office has developed a Global Sounding System known as GLOSS (Gadd *et al.* 1994) along the lines of the LASS system but using an iterative non-linear retrieval scheme (Eyre 1989). This runs on the Cray immediately before each Global Model data assimilation rather than at the time of receipt of the data as in the LASS system. A similar system is operational at ECMWF (Eyre *et al.* 1993).

2. Correction for biases

Whether a linear or non-linear retrieval scheme is used, a vital component is the assumed background profile of temperature and moisture. This should be as close as possible to the actual state of the atmosphere as retrieval schemes are based on linearisation of the problem when expressed in terms of deviations from this profile. In the original LASS scheme (Eyre and Jerrett 1982) a climatological background profile was used but since 1988 this has been replaced by a forecast from the operational model. Although the use of a forecast means that the retrievals have error characteristics that are not independent of the model, experience has shown that the better quality of a short-period forecast over climatology leads to a better retrieval in most respects. A model forecast has

now become the standard source of background profiles for satellite retrieval work in the Office.

The theory behind most retrieval techniques assumes that the errors in the observations and background profile have zero mean, *i.e.* they contain no systematic bias. If any biases are actually present due to unaccounted instrumental characteristics, limitations of the radiative transfer calculations etc., these can be preserved in the model, being passed from retrieval to model through the data assimilation and from model to retrieval through the background profile. To prevent such biases accumulating in the model, a bias correction is applied before the retrieval is performed to compensate for systematic differences between the observations and their background estimates. In GLOSS the technique used is a regression method developed at ECMWF (Eyre 1992) incorporating an air-mass dependence. Regression coefficients are updated each month using statistics for the previous month and are designed to minimise the difference between the measurement from each channel and the corresponding value which would be obtained from an error-free instrument observing the background profile.

3. Residual biases over land

The performance of the bias correction scheme can be monitored by computing the mean and standard deviation of the bias-corrected difference between the observations and the computed background values for a sample of data. If the bias correction has been applied correctly we should expect to see mean differences close to zero over the whole globe and a small standard deviation compatible with the observation and background noise levels.

For most channels the geographical variation of the differences over the sea meets these expectations (the regression coefficients for the bias correction are computed using data over the sea only) but over the tropical land masses much larger differences are found. For example, Fig,2 shows the mean observation-minus-background differences for channel 7 of the NOAA-11 satellite for the period 4-23 January 1994. The data are expressed as 'brightness temperatures', the temperature of a black-body which would give an energy level at the satellite equal to that observed. (In this and subsequent figures, mean differences were computed for 15° by 15° boxes over the globe by fitting a theoretical curve to the data distribution for each box ignoring extereme data points (Barwell 1992).) The chart shows large non-zero biases over most of the major land masses and polar regions.

Figure 3 shows similar charts for the NOAA-12 satellite for channels 5, 6, 7 and 10. These channels are arranged in increasing order of atmospheric transparency. and show that the channels which receive radiation from deeper in the atmosphere are most affected.

Although the same is true of NOAA-11, the details of the pattern differ as can be seen by comparing channel 7 for NOAA-11 (Fig.2) and the same channel for NOAA-12 (Fig.3(c)). Note especially the difference of pattern and the sign of the features over North Africa. Figure 4 shows the mean difference between the retrieved and background NOAA-11 surface ('skin') temperatures and the corresponding difference for the 1000hPa temperatures. These indicate that the surface is mainly responsible for the differences.

4. Diurnal variation of surface temperature

The evidence presented above suggests that the observational biases found over the land masses might be due to the diurnal cycle of surface temperature. To understand this more fully some explanation of the origin of the background profiles for LASS and GLOSS is necessary.

As indicated above, both LASS and GLOSS use short-period forecasts from the Meteorological Office Unified Model (Cullen 1993) as the source of background profiles for the retrieval but there is a difference in the way the background is derived. When processing a LASS pass, forecasts from the limited-area version of the Unified Model are extracted for the beginning and end of the three-hour period which includes the nominal time of the pass, and the background is obtained by linear interpolation within the period to the pass time. For GLOSS however, satellite data for a six-hour time window centred on the Global Model's analysis time (00Z, 06Z, 12Z or 18Z) are processed together using as background the model's six-hour forecast for the analysis time without any interpolation. The result is that whereas in LASS the background is for the time of the start of the pass as received at Lasham and therefore has a maximum timing error of the duration of a pass (about 20 minutes), for GLOSS the background can be up to three hours different from the data time.

Within a three-hour time interval the change in surface temperature in the tropics and sub-tropics can be considerable. The change will vary for different types of surface being negligible over the sea and largest over desert regions where cloud and vegetation cover are at a minimum. Such variations would be easily noticed in TOVS data since the channels observing the lower regions of the troposphere are particularly sensitive to surface temperature. Differences from background in these channels could easily appear as biases since the satellites are in sun-synchronous orbits which cross the equator at the same local time each orbit. This could also explain the difference between NOAA-11 and NOAA-12 since their equator crossing times differ by about three hours. For example. over West Africa the afternoon NOAA-11 passes occur at about 1600Z whereas NOAA-12 passes are at about 1900Z. Both will use background profiles for 1800Z. As the surface is rapidly cooling at this time we expect the NOAA-11 observations to be warmer than background

and NOAA-12 to be colder than background. This is in agreement with the channel 7 differences (Figs. 2 and 3(c)).

5. Orbit-by-orbit comparison with background

To investigate the effect of diurnal variations of surface temperature further, three geographical areas were selected for more detailed study. These were chosen to be in regions where there are large differences in Fig.2 or Fig.3. Other considerations were need for a surface with a fairly uniform altitude to minimise local variations in surface temperature and differences between model and actual topography, and the availability of cloud-free retrievals on most or all orbits over a period of several days. Although the most suitable areas are desert regions a tropical rain forest area was also chosen for comparison.

The three areas chosen are indicated on the maps in Figure 5 and are listed below with the data periods used.

(a) Western Australia (20-27°S, 123-128°E; 09Z 7/12/93 to 12Z 9/12/93)

(b) Gobi Desert, Mongolia (43-49°N, 105-115°E; 00Z3/12/93 to 12Z 7/112/93)

(c) Lower Amazon basin, Brazil (3-9°N, 40-60°W; 18Z 1/12/93 to 12Z 3/12/93)

In (c) only data over the land were used in the investigation.

For each area the GLOSS retrieved surface temperature was compared with the background surface temperature from the model for each orbit during the study period. Only data for fields of view designated cloud-free by NESDIS were used as retrievals in cloudy fields of view did not use HIRS data which contains the channels most affected by surface temperature. The mean retrieved value for the area was estimated subjectively from charts and was assigned to the mean observation time. Mean background values were estimated similarly and were assigned to the appropriate model time (the nearest multiple of six hours to the data time).

6. Results

The resulting graphs of surface temperature against time are shown in Figures 6, 7 and 8 in which model background values are indicated by circles and retrieved values by "+" for the NOAA-11 satellite and " " for NOAA-12. Periods of darkness as given by the *Nautical Almanac* (H.M.S.O. 1992) are indicated by thickened sections of the horizontal axis. Curves are drawn subjectively through the background values so as to make the maximum temperature in mid-afternoon and the minimum temperature just before sunrise where this fits the data.

The curve for the Western Australia area (Figure 6) shows a clear diurnal cycle of surface temperature in the model with an amplitude of about 40°K. The satellite-retrieved temperatures follow this curve closely indicating that the diurnal cycle noticeably affects the observations and has a similar variation to that in the model. However, this does not prevent large differences between model and retrieval due to the time difference between background and observation. For example, the NOAA-11 pass at 0850Z on 8th December shows a mean retrieved surface temperature of 325.7°K whereas the background (taken from the model forecast valid at 0600Z) is 333.5°K, *i.e.* nearly 8°K warmer. The time difference in this case is 2 hours 40 minutes, close to the maximum difference of 3 hours at a time when the ground is still warming up to the afternoon maximum temperature. Several other cases can be seen in the figure where the temperature difference between retrieval and background is around 4-7°K, the sign of the difference always being consistent with the sign of the time difference and the stage of the diurnal cycle.

For the Gobi desert (Fig.7) orbits were studied for a period of about five days. Some gaps in the curve occur where retrievals were not available. Although there is not such close agreement between the curve and the retrieved values as for Western Australia, there is still an indication of the diurnal cycle in the retrievals especially during the daytime. The amplitude of the cycle is about 15°K, less then half of that in Figure 6. As before, some temperature differences between retrieval and background can be clearly assigned to the time difference between data and model. Another factor responsible for temperature differences is the increased day-to-day variability which might be expected at latitudes about 45° from the equator. (Also, the trend of the curve during the latter part of the night is influenced by the orbital times of the NOAA-11 satellite. Passes around 19-21Z which use the 18Z background occur in the extreme east of the area where the ground is lowest whereas those for 21-23Z which use the 00Z background are over higher ground in the west. This may give rise to the kink in the background curve on some nights.)

In spite of the very different nature of the surface, the curve for the South American region (Fig.8) is very similar to the Australian one (Fig.6) although the range of temperature is much smaller (about 17°K instead of 40°K). This would be expected from the vegetated surface and greater afternoon cloud cover over the rain forest but the diurnal temperature cycle is as clear as it was for Australia and the agreement between curve and retrievals is just as close.

7. Conclusions

The results described in section 6 indicate that over land subject to a marked diurnal cycle of surface temperature, the cycle is detectable in satellite observations used for

retrieving atmospheric temperature profiles. The effect is noticeable in the tropics and over sub-tropical desert regions where synoptic activity and other influences are at a minimum.

Several channels on current operational satellite sounding instruments receive a considerable portion of their signal direct from the surface. If the background surface temperature, taken from a short-period model forecast, is valid for a time different from that of the data at a time of day when the temperature is rapidly changing, the retrieval is constrained to make substantial near-surface changes to the background to fit the observations. In most cases the retrieved surface temperature will be an improvement over the background but the finite width of the weighting functions and the assumed vertical correlations can result in additional errors in the atmospheric profile at low levels. In fact it is generally true that any reduction in quality of the background is bound to impair the quality of the retrieval.

The work described in this report suggests that GLOSS retrievals can be improved by the use of a time-interpolated background profile as used by LASS. Over the sea the diurnal change in surface temperature is negligible and the benefits may be smaller though some advantage may be gained where conditions are changing rapidly (a sudden change of air mass, for example). Over land and to a lesser extent over sea ice, the benefits of time interpolation are somewhat greater.

GLOSS retrievals are produced over land as well as sea although there are no plans at the moment to assimilate retrievals over land because of their poorer quality. Figs. 6-8 show that in areas with a substantial diurnal temperature cycle, linear interpolation between fields six hours apart will generate improvements to the background profile which can be passed on to the retrieval. However. a method which follows the daily cycle may be required to obtain the best results over land. This could be achieved by dumping low-level fields from the model at intervals more frequent than six hours or by assuming a mean daily cycle to correct the model fields for differences from data time.

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Figure 1. Locations of satellite sounding data for one day (21 February 1994, 78244 observations).

Mean brightness temperature differences for channel 7 on NOAA-11.
Data for cloud-free fields of view, 4-23 January 1994.

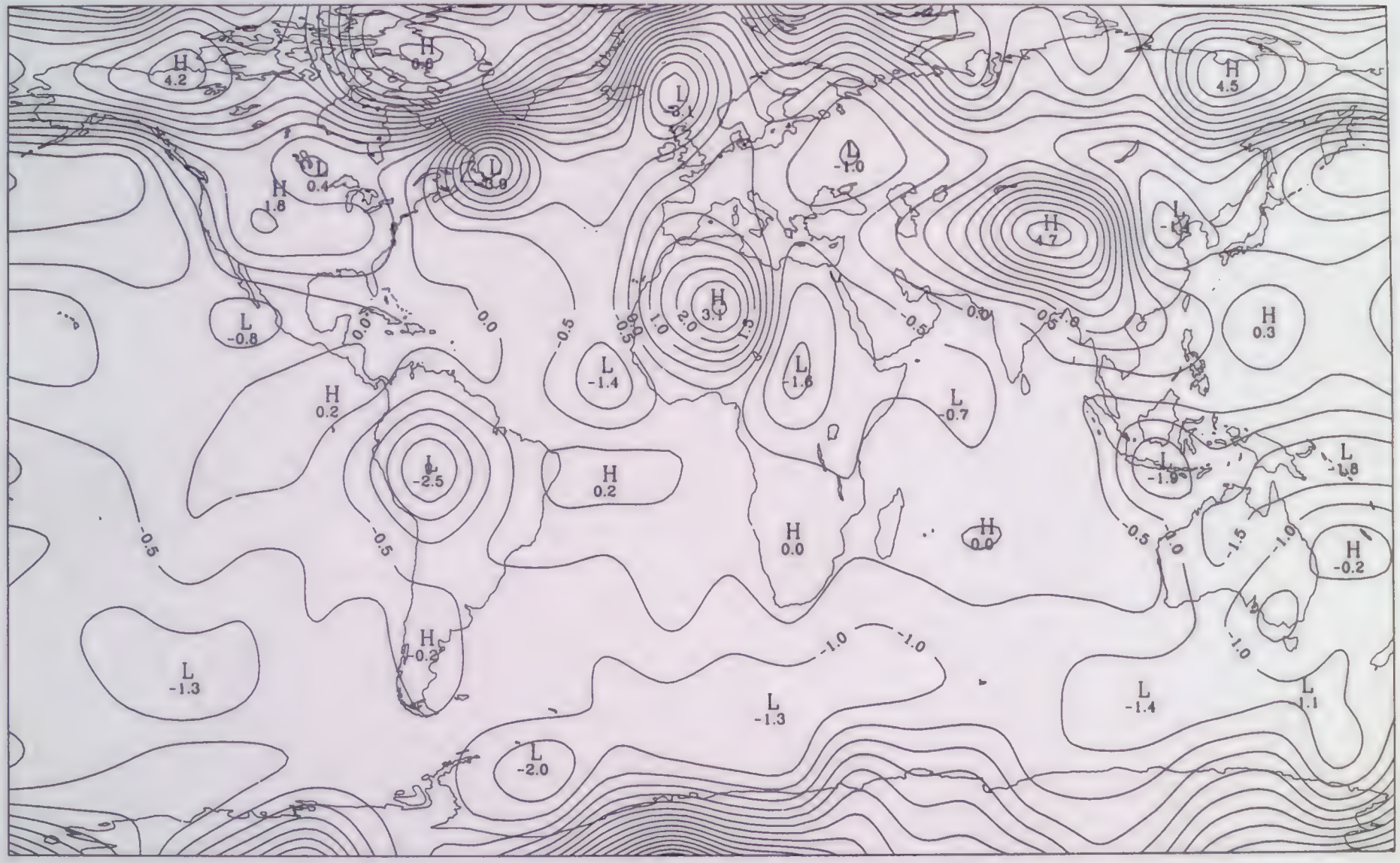
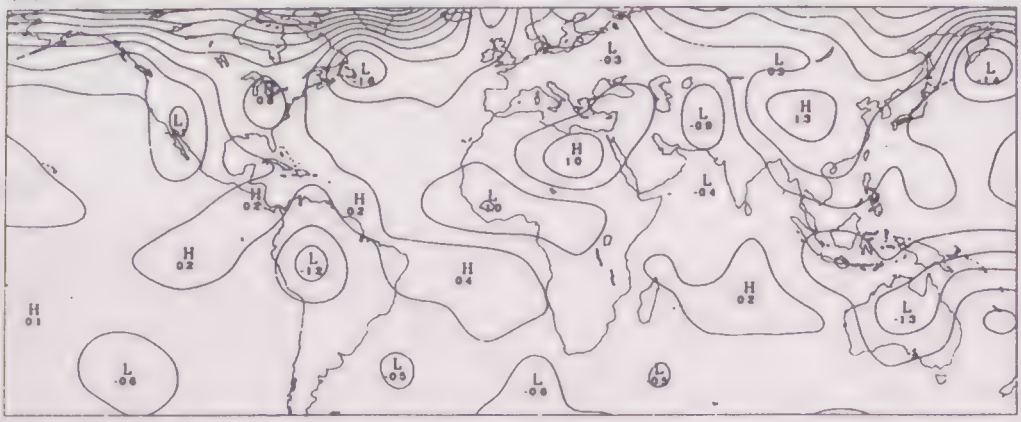


Figure 2. Mean observation-minus-background brightness temperature differences for NOAA-11 channel 7, 4-23 January 1994. Chart is based on means for 15° boxes. Contour interval is 0.5°K.

Mean brightness temperature differences for NOAA-12, 4-23 January 1994.

(a) Channel 5

(b) Channel 6

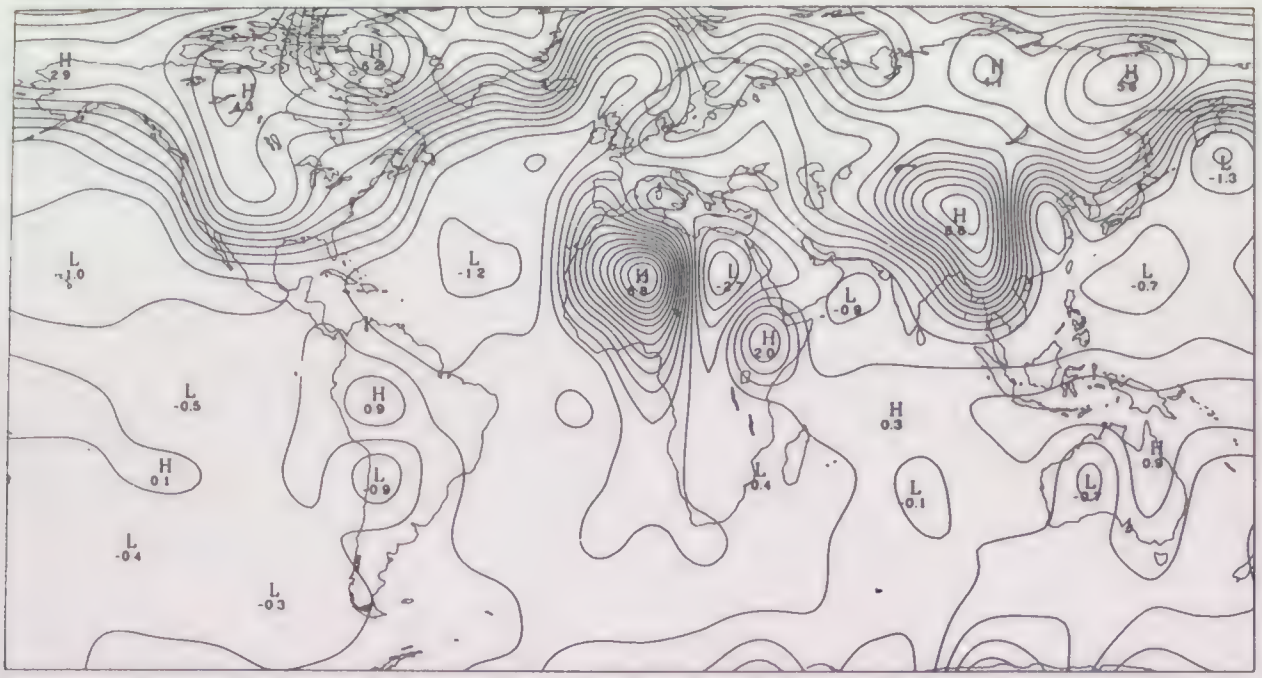


(c) Channel 7

(d) Channel 10

Figure 3. Mean observation-minus-background brightness temperature differences for NOAA-12, 4-23 January 1994. (a) Channel 5, (b) Channel 6, (c) Channel 7, (d) Channel 10. Charts are based on means for 15° boxes. Contour interval is 0.5°K.

(a) (Retrieved-background) surface temperature differences.



(b) (Retrieved-background) 1000hPa temperature differences.

Figure 4. Mean retrieved-minus-background temperature for NOAA-11, 4-23 January 1994 for (a) surface, and (b) 1000 hPa. Charts are based on means for 15° boxes. Contour interval is 0.5°K.

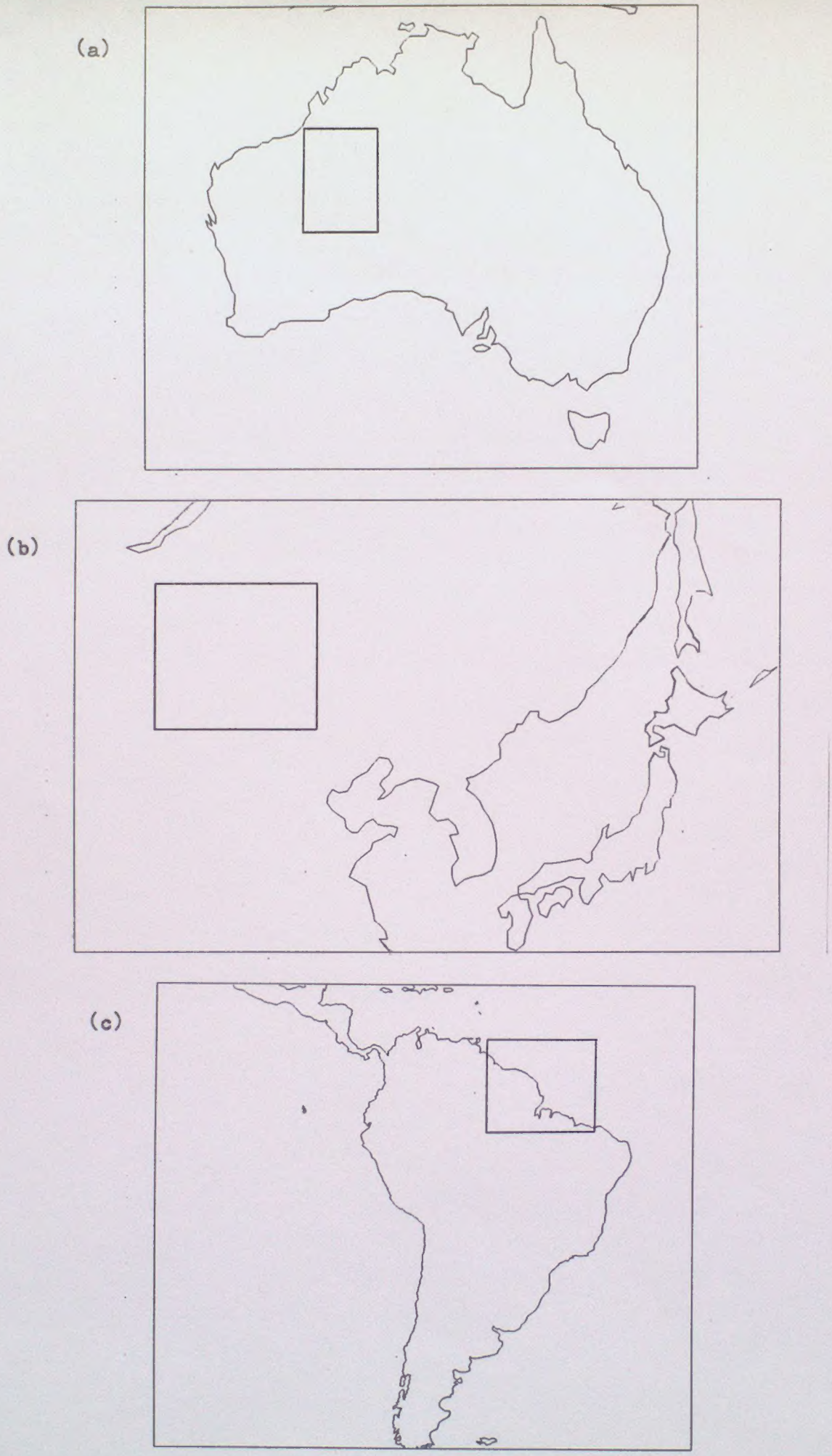


Figure 5. Areas used for study of individual orbits. (a) Western Australia, 20-27S, 123-128E, (b) Gobi Desert, Mongolia, 43-49N, 105-115E, (c) Lower Amazon Basin, Brazil, 3-9N, 40-60W.

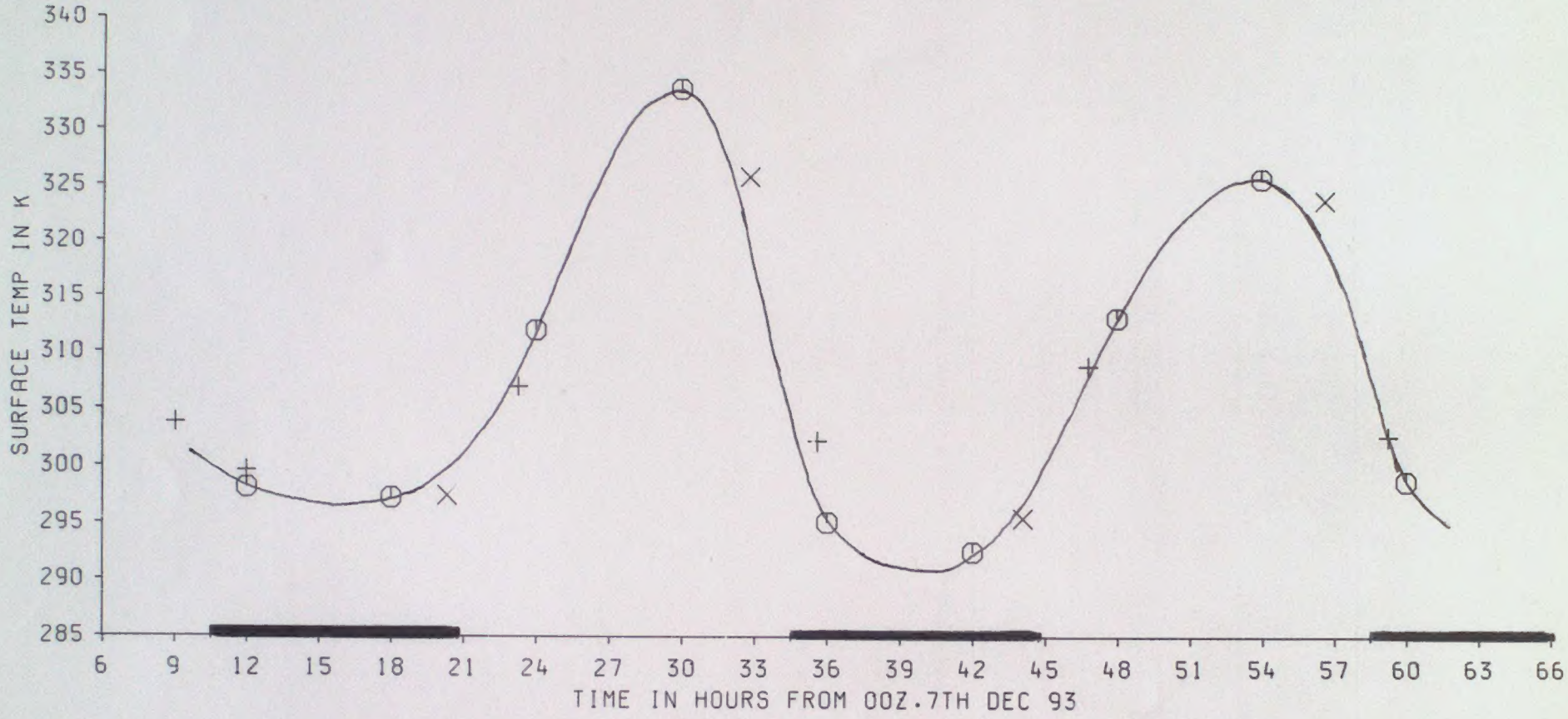


Figure 6. Surface temperatures for Western Australia (see Fig.5(a)), 06Z 7 December to 18Z 9 December 1993. ('O' - model background, '+' - NOAA-11 retrievals, 'X' - NOAA-12 retrievals.) Periods of darkness are indicated by thick bars on the horizontal axis.

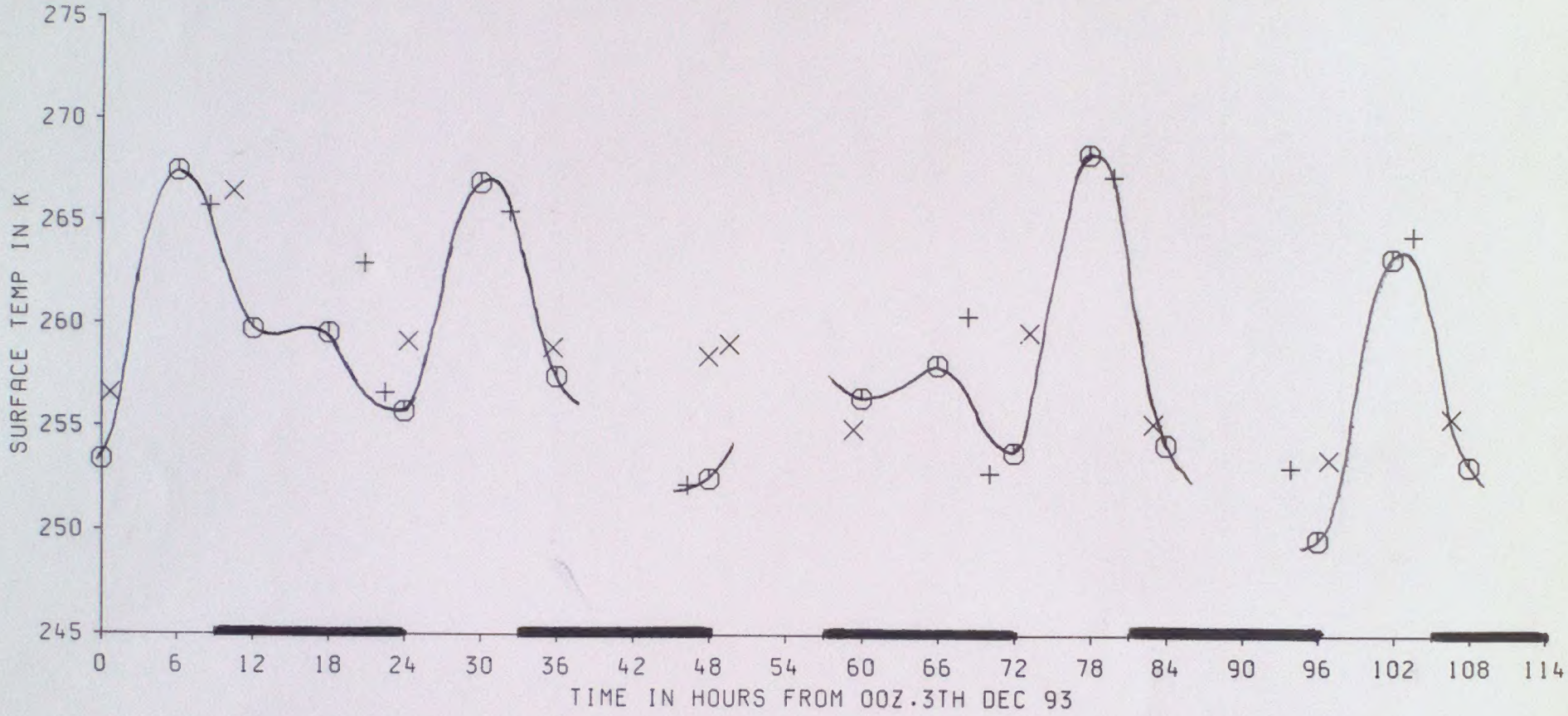


Figure 7. As Fig.6 but for Gobi Desert (see Fig.5(b)), 00Z 3 December to 18Z 7 December 1993.

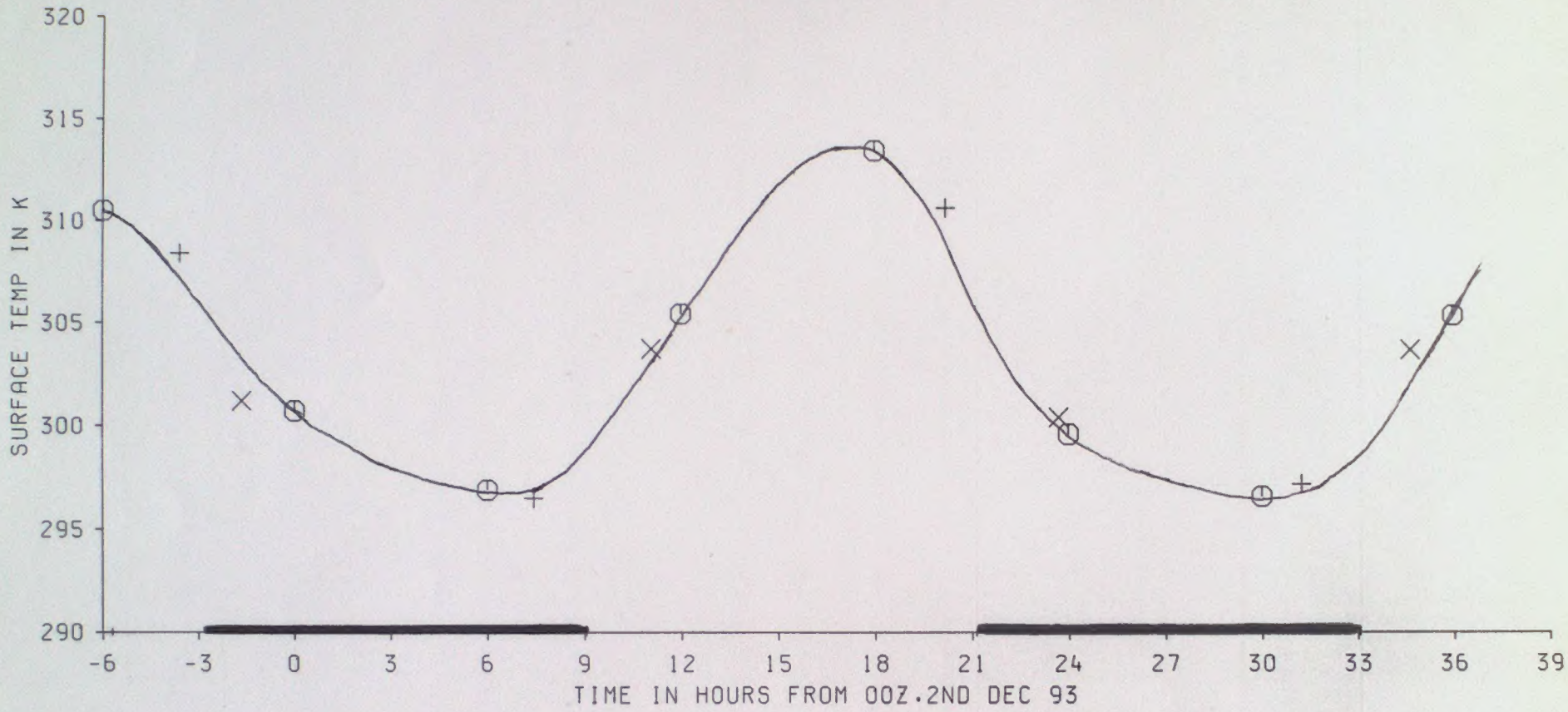


Figure 8. As Fig.6 but for Lower Amazon Basin (see Fig.5(c)), 18Z 1 December to 15Z 3 December 1993.